Resorbable poly(L-lactide) bone plates and screws

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CHAPTER 3

COMPUTER AIDED OPTIMIZATION OF CHOICE AND POSITIONING OF BONE PLATES AND SCREWS USED FOR INTERNAL FIXATION OF MANDIBULAR FRACTURES

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This chapter has been submitted for publication in the Journal of Oral and Maxillofacial Surgery

SUMMARY

The present study describes a biomechanical integrated model of the mandibular system in which the upper and lower jaw, the masticatory muscles and the temporomandibular joints are regarded as one system. In this model strains in plate-osteosynthesis devices for internal fixation of mandibular fractures can be minimized by optimizing their positions. The model evaluates maximal bite force strategies on all possible dental elements, using a linear programming technique and a muscle architecture model, resulting in muscle recruitment patterns. The shape of a 'standard' lower jaw is digitized by means of a 3D coordinate retrieval device and drawn on a computer screen after changing its dimensions according to the clinical case at hand. The 3D location of the fracture can be indicated on the screen as well as the anatomical restrictions for screw placement. Osteosynthesis devices can be indicated in terms of dimensions, number and material properties.

INTRODUCTION

For many years, oral and maxillofacial surgeons have used several types of fracture fixation devices. Point of concern has always been the strength of these devices in order to enable undisturbed fracture healing. Studies concerning the mechanical properties and stability have clearly demonstrated that the plate-osteosyntheses used nowadays are more stable than the wire fixations used a few decades ago.[1] In these studies, the AO and Champy bone plates were found to be more resistant to vertically bending forces of the mandible than wire fixations.[2-4]

Criteria, theories and mathematical models predominantly referring to the mandible, were developed in the past to formulate biomechanical justification of the positioning of the different fixation devices. Based on simple mathematical models and photoelastic analysis, using polarized light on araldite bars representing the lower jaw, Champy et al.[5] concluded that tension zones occurred at the upper border and compression areas at the lower border of the mandible. The incisor and canine regions revealed a zone of torsion moments. These tension and pressure zones were confirmed in other studies which were based on the same assumptions.[6,7] However, because of many exclusions, the indications for the use of the different types of plate devices must be assessed critically in each fracture. For instance, topographic restrictions and specific indications for mono- or bi-cortical osteosynthesis should be taken into account.[5,7] Age (under 13 years), comminuted and infected fractures are criteria for not using miniplates.[8]

Additionally, several studies were performed on the intact human masticatory system in which the upper and lower jaw, the masticatory muscles and the temporomandibular joints were regarded as one system.[9-17] In these studies, the optimal directions and magnitudes of the bite forces acting on the mandible in different positions to the occlusal plane were analyzed. At the same time, some understanding about muscle recruitment as a way to optimize efficiency or maximize bite forces has been provided. The generated models have been useful because electromyographic (EMG) measurements which can predict the possible influence of the acting muscles on the magnitude of bite force were hard to obtain.

After the development of resorbable poly(L-lactide) (PLLA) plates and screws used as osteosynthesis, which revealed breakage of the polymeric plate at 50% of the tensile force which could be applied to the Champy miniplates,[18,19] we felt the need to develop an integrated computer model that could predict the forces exerted on the human mandibular system. Until now, no integration of the two mentioned types of studies has taken place.

For the rat an integrated model of the jaw system had already been formulated by Otten.[20] This model calculates movements based on muscle recruitment and contains the morphometrics of bony elements, jaw joints and muscles.[21] Since maximal load across the fracture in a jaw occurs in static biting conditions (see discussion), this model can easily be simplified and fed with human morphometrical data. Data acquisition from human material is a separate problem to be handled. The main problem to be solved is to calculate loads across the fracture, and the consequent elastic deformation of applied osteosyntheses. A complete graphics environment should be formulated to have access to the model through visual and manual interaction by which fractures can be indicated, osteosynthesis properties can be introduced, characteristics of the patient can be presented and by which the software can draw resulting solutions of optimal positions and selection of osteosyntheses.

The aims of such a modelling enterprise in our research program are:
Firstly to analyze the possibilities for application of resorbable osteosyntheses. Secondly to understand the factors determining the loads across a fracture and the magnitude and direction of forces on osteosyntheses. Thirdly to be able to make a well founded decision within a reasonable time frame about the optimal localization and direction of osteosyntheses in individual cases to neutralize these forces.

In summary, a high level of integration of knowledge from different fields is needed:

- A method to acquire 3D data from the human jaw system.
- A method to display a reconstruction of a human lower jaw on a computer screen.
- Muscle physiological data and muscle architectural data from the human jaw system.
- A linear programming technique for the calculation of optimal recruitment patterns of the muscles at given bite point locations.
- A method to indicate on a computer screen the 3D location, orientation and shape of a random fracture.
- A method to relate the end displacements and rotations of elastic elements with the resulting end force and torque vectors and internal maximal strains.
- A high dimensional search method in the space of possible osteosyntheses placements, looking for minimal strain and chance of failure.
- Information on the areas that allow good anchorage of the osteosynthesis screws in the human jaw.

MATERIAL AND METHODS

The software package called 'JawKit', was written by Otten on and for the Mac II line of computers manufactured by Apple, because of their speed, graphics environment and good value. The MPW 3.0 environment was used for programming and debugging. Most of the graphics was taken from a computer reconstruction package called MacReco, (Fig. 1).[22] Full profit was obtained from the Macintosh user interface (mouse and menu driven) and the high resolution graphics on a laserwriter (Apple Laserwriter II NTX), using halftone simulation techniques (Fig. 3).

The data on human muscle architecture were taken from Weijs and Hillen,[23] summarized by Koolstra et al.[17] In order to digitize the three-dimensional surface of a 'standard' human mandible, a digital position recording system was developed (Fig. 2), which consists of a rotating table on which the lower jaw can be mounted, fitted with an optical potentiometer (HEDS 7500) with a resolution of 0.1 degrees. A pen is fixed to two sliding bars with steel wires, also connected to optical potentiometers (HEDS 7500) with a resolution of 0.1 mm. With the pen any point on the lower jaw can be indicated from which a unique set of three cylindrical coordinates (two positions and one angle) is shown on a digital display. An interface connects the potentiometers to a microcomputer (Tandy 64k color computer), that collects the data. From the small computer, data can be sent to a Mac II computer and made accessible to the graphics software after conversion from cylindrical coordinates to orthogonal coordinates and resectioning in parallel equidistant planes.

One of the greater deficiencies of our knowledge concerning motor control of the human lower jaw is that of muscle recruitment patterns. Measurements are very hard to obtain, particularly of the pterygoid muscles. However, for an optimization model as offered in the present paper, such knowledge is of vital importance. To get round that problem, a number of investigators[16,17] have modeled the lower jaw as a static system, supported by the jaw joints and a bite point location and balanced by a redundant set of muscle forces (there are more independent muscle units than degrees of freedom of the lower jaw). In order to find a realistic solution to this problem, an optimization criterion is needed. The criterion employed by Osborn & Baragar[16] gave rise to the so-called staircase phenomenon, which is the recruitment of more and more muscle units at increasing bite forces one after the other, which however is not a natural phenomenon. From EMG measurements we know that recruitment involves a gradual increase in muscle activity at increasing bite force in a given bite force direction while the pattern of muscle activity as such does not change.[24] Koolstra et al.[17] based their model on these findings and purely looked for the optimal recruitment pattern, using a linear programming technique by minimizing the largest recruitment of any of the muscles. This ensures that a recruitment pattern is found that not only balances the lower jaw, but also provides the highest bite force attainable. Their method was used in the present software (indicated by 'Optimal Bite Software' in Fig. 1) to get round the lack of complete data sets of recruitment patterns. The linear programming software was taken from Press et al.[25]

The input data for this method consists of the insertions of the jaw muscles, their working line directions, their maximum isometric forces, the directions of the jaw joint load vectors and the location and direction of the bite force. The same data Koolstra

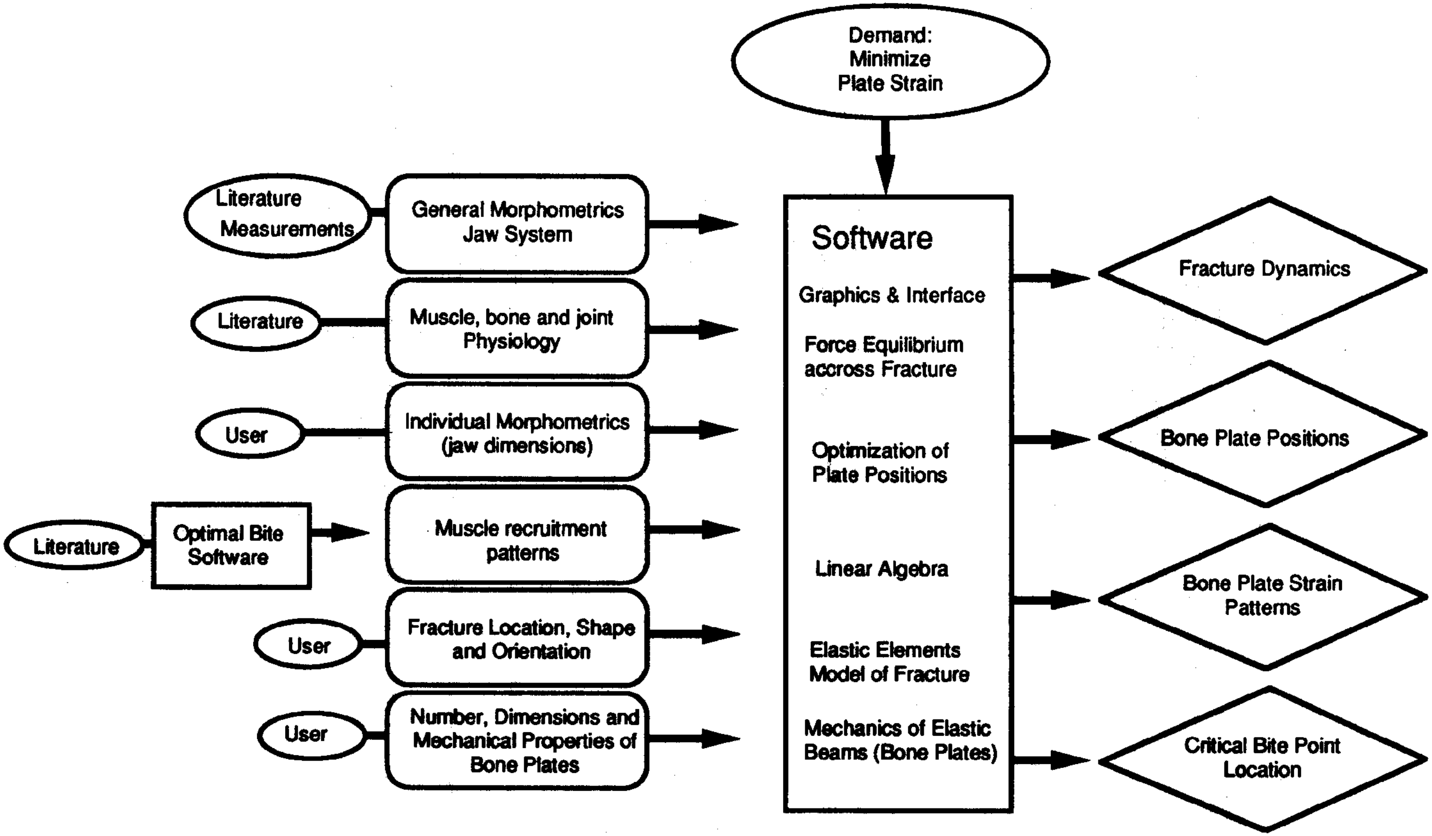

Figure 1 Scheme of input, output and units of 'JawKit', a software package designed to optimize position and device choice of boneplates in mandibular fractures. Elliptic shapes indicate input source, rounded rectangles input, rectangles software and diamond shapes output.

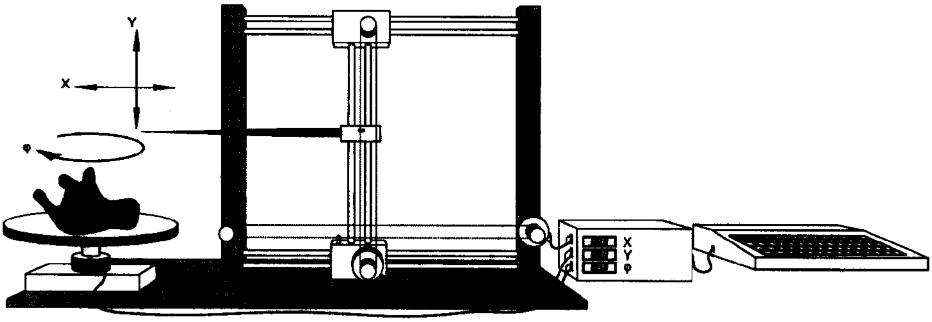

Figure 2 A digital position recording system, designed to trace the three-dimensional shape of surfaces of the 'standard' mandible. The mandible is mounted on a platform which can be rotated (the angle (φ) of rotation is the third coordinate). A pin can be moved up and down and also forward and backward in one plane (providing the first and second coordinate; X and Y), so that any point on the mandible can be indicated. Coordinate groups are transferred to a microcomputer.

et al.[17] used were put into our model, transformed to the data set from the jaw measured with the digital position recording system described above. As a starting point an at random chosen, 'normal looking', male Caucasian young adult mandible with complete dentition was obtained at dissection. The mandible was prepared using standard maceration procedures.

The software allows deformation of the 'standard' lower jaw that was digitized, to accommodate specific dimensions of a case at hand. There are four parameters that can be changed: the width, height and depth of the lower jaw and an angular offset in the parasagittal plane. These parameters can be determined on tracings of standardized roentgenographs (cephalograms, panoramic views with a known magnification, 3D CT-scans) by the measurement of mandibular intergonial breadth (gonion-gonion), mandibular height (distance between the plane of the lower border and the tangent through the condyle parallel to the lower border), mandibular corpus length (gonion-menton) and jaw angle (between inferior and posterior margins of the mandible). Most of the individual differences found can be suitably described with these parameters, regarding the level of detail of the other parameters used in the software.

A user interface was written with which it is possible to indicate the location and shape of a random fracture. A three dimensional reconstruction of the lower jaw is drawn on a computer screen from a desired viewpoint and with a desired view angle. With a mouse-driven interface, points can be indicated on the lower jaw. Detailed serration of the fracture can also be described in this way. This important factor is included in the biomechanical analysis of the fracture. The user can indicate the number, dimensions and mechanical properties of the bone plates, so that any type of bone plate can be simulated and tested. With the above mentioned mouse-driven interface, curves can be indicated on the outer surface of the lower jaw at both sides of the fracture, that are acceptable anchorage sites for the bone screws for fixation of the plate. Only along these curves, solutions are attempted to be found.

The outer cortex is strong and thick (average thickness 5 mm).[8] This enables good anchorage of the osteosynthesis screws. In the tooth-bearing alveolar process the anatomy of the roots of the teeth and the structure of the bone do not allow screw fixations in this region. The anatomy of the area along the alveolar nerve and around the mental foramen should also be taken into account.

A bone plate is simplified to a rectangular beam element, a well studied concept in structural mechanics. Of such a beam element, the formulas between the displacements and rotations of the fixed end facets on the one hand and the forces and torques acting on these end facets on the other, have been extracted from Popov.[26]

These formulas describe the behavior of a rectangular beam element under complex loads as a combination of torsional, bending, s-shaped and linear deformations. No attempt is made to simulate more complex shapes of bone plates, since it is assumed that the design of the bone plates is aimed at avoiding internal weak points where failure is bound to happen. Consequently, the bone plate should have evenly distributed strength and a simulation of the middle part of the bone plate should suffice, assuming perfect fixation of the plate to the bony elements. This assumption implies that the strength of the screws and their anchorage in the bone should not be a limitation for the bone plate strength.

A major task in completing the software was to design an algorithm that can calculate the displacements and rotations across the fracture at a given position of one or more bone plates under the load of an external force and torque. A straightforward method would be to use a finite elements description of the elastic combination of bones and plates, but that would require too many data from a living human being to be attainable. Therefore it was decided to use an elastic elements method designed to suit the given detail of the elastic combination of bones and plates.

First the fracture surface is divided into a number of triangles. Each of the bony triangles is considered to provide an elastic resistance for its counterpart at the other side of the fracture at right angles to its surface. This elastic modulus is taken to be 19.4 GPa (Measurements on fresh human mandibles by Ashman and Bushkirk[27]). In this way a number of push springs is defined in space with different directions. Each of the springs has a zero length of 25 mm, being the average distance between the points of insertion of the jaw muscles, the joint vectors and bite vectors on the one hand and a large number of possible fractures on the other. This number is not very critical because of the high elastic modulus of bone, so that displacements remain small when two bony surfaces are compressed together with the forces that can be generated by the jaw muscles. Together with the bone plates in position and in combination with their mechanical properties, this system has elastic energy as a function of three-dimensional displacements and rotations (six degrees of freedom) at a given external force and torque acting on the system. A minimum in this energy function is a solution in which all forces and torques cancel each other. This minimum is found by using a polytope search algorithm[28] in the space of displacements and rotations with zero displacements and rotations as a starting point for the search.

After finding the nearest minimum, the compressing forces on the bone, the displacements at the fracture, the deformations of the bone plates and the forces and torques generated by the bone plates are known. Moreover, the maximal internal strain somewhere in any of the bone plates is known, which is a variable that needs to be minimized in order to obtain a minimal chance of bone plate fracture. This bone plate strain can be minimized by looking for the optimal placement of the bone plates, since that placement influences the bone plate strain. Because of the rather complex mathematical relation between maximal bone plate strain and the coordinates of placement of the anchorage points of the bone plates, a gridsearch strategy was used preceding a polytope search algorithm. The gridsearch strategy simply places a multidimensional grid in the space of coordinates of placement of the anchorage points of the bone plates and calculates the maximal bone plate strain at each of the grid points. After that, the point at which the lowest maximal bone plate strain occurs is selected as a starting point for the polytope search method, which looks for the closest actual minimum in maximal bone plate strain. The processing time needed on a Mac IIx computer is about 5 min. for a fracture fixation proposal with one bone plate and 30 min. for an osteosynthesis with two bone plates, depending heavily on the detail of description of the type of fracture and the bone plate anchorage curves.

RESULTS

Figure 3 shows a typical result of a computerized search for optimal positions of bone plates and screws. Muscle forces, joint vectors, one bite vector (of the 13 divided over the dental elements) and loads on plates and bone at the site of the fracture are presented. Only one bite vector is drawn, but the optimization was done with the whole set of possible bite point locations on all dental elements in directions perpendicular to the occlusal plane. Robustness analyses showed that directions of the bite vector within a cone with an opening angle of 30 degrees and an axial direction perpendicular to the occlusal plane gave very similar results.

Figure 3 shows a serrated fracture, of which the fixation demands differ from those of a smooth fracture shown in Figure 4. The serration is able to take up certain components of the torque and also to a certain extend shear forces, making the fixation task of the bone plate easier. As can be seen in the figure, the optimal solution for the position of the plate is different for the two cases. The image of the lower jaw as given in the Figures 3 and 4 is the result of a number of mathematical and graphical operations. Each of these operations brings about small artifacts in the resulting image, so that small deviations from the actual lower jaw occur. These deviations however are within the precision of the other data (on muscles for instance) and operations (search methods) used.

As an example, the mechanical properties and dimensions were used of a high molecular weight as-polymerized Poly(L-lactide), which has been tested in several studies.[18,29-31] In the serrated case the maximal strain occurring in any part of the bone plate is 1.08% whereas in the smooth case the maximal strain amounts to 1.56%, which is beyond the tolerance of the material as it is present in the used plate dimensions.

It must be stressed, however, that the calculations are based on optimal muscle recruitment patterns, generating maximal bite forces. Gerlach et al.[32] already indicated that patients two days after operations, in which miniplates were mounted, produce only 17% of maximal bite force, increasing to about 50% after 4 weeks, suggesting strong inhibition of the normal muscle recruitment levels.

After some trials with our software it appeared that not only the absolute strength of bone plates is of relevance to their success but also their shape: broad flat plates

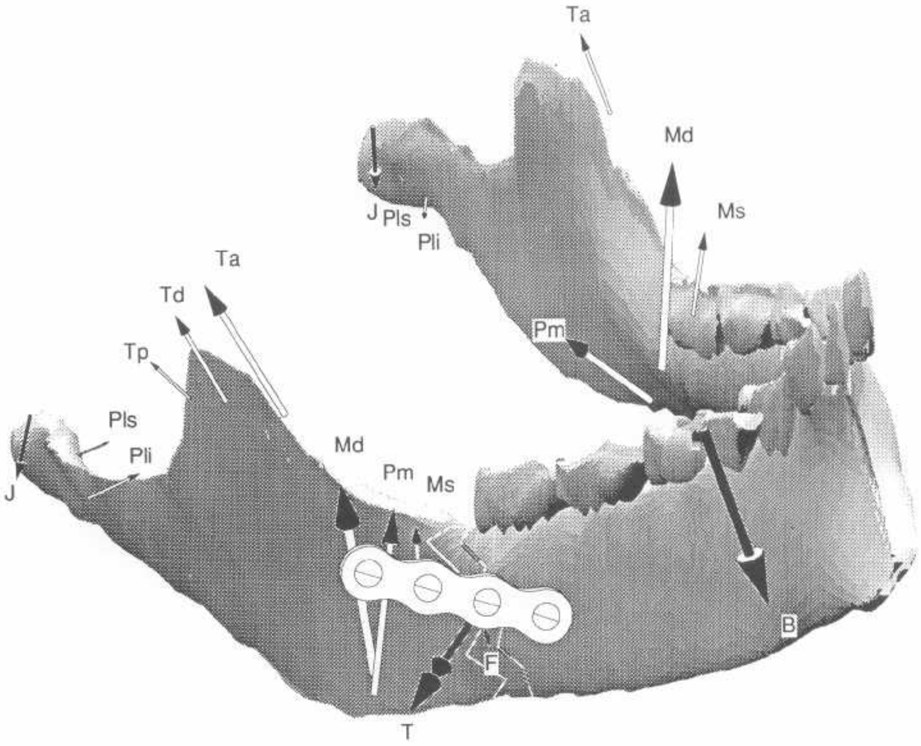

Figure 3 Three-dimensional reconstruction of a human lower jaw with muscle forces (white arrows), joint loads (J) and bite force (B) (black arrows). The black forces have been scaled down by a factor of 3.75 relative to the muscle forces.
The characters in the reconstruction represent the following muscle forces: (Md) and (Ms), deep and superficial masseter; (Pm), medial pterygoid; (Pli) and (Pls), inferior and superficial lateral pterygoid; (Ta), (Tp) and (Td), anterior, posterior and deep temporalis.
A serrated fracture (F) (dashed lingually) is indicated on which a force and torque acts as a result of the force equilibrium of muscle forces and loads. The torque (T) is drawn as a double headed arrow and is a result of the worst case bite point selection. Only one bite point has been drawn for clarity. A boneplate is drawn by the computer. The optimal position of the bone plate was calculated by the software presented in this paper.

are able to withstand deformation in a plane tangential to the surface of the lower jaw very well. These plates were used for most types of fractures tested. This is very important because in cases in which one narrow plate can not give sufficient stabilizing of a fracture, and two would have been indicated, a single broad plate can suffice.

An extra possibility of the software is to calculate fracture mobility. For instance in the case of Figure 3, an axial movement of 0.02 mm occurs, whereas movements in the plane of the fracture did not exceed 0.1 mm. This may be of help in studying the relation between fracture mobility and fracture healing.

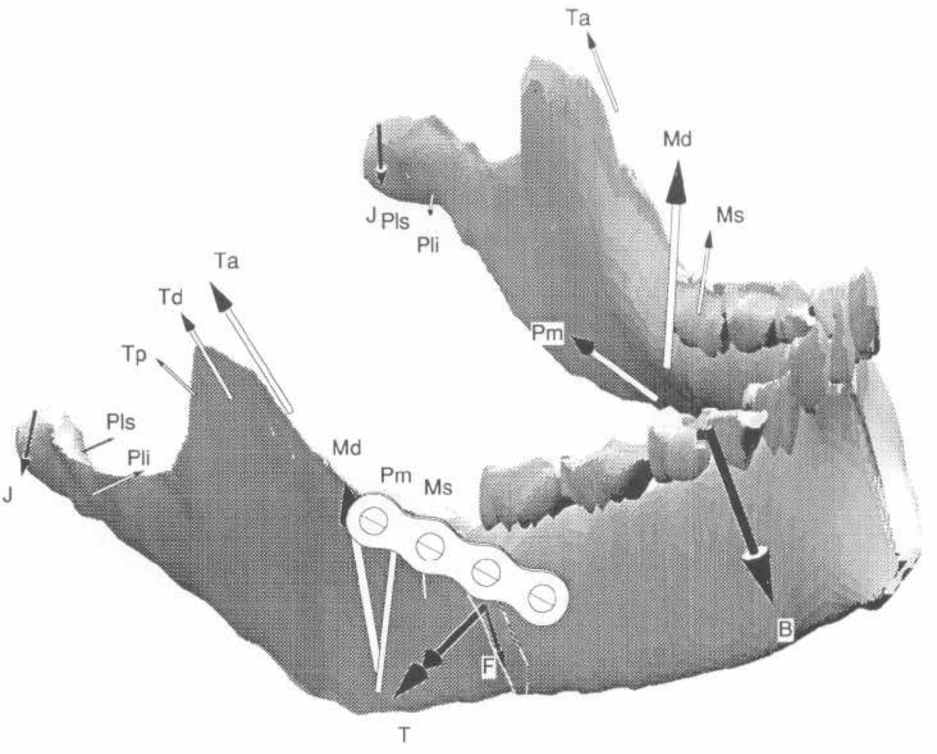

Figure 4 Boneplate optimized for a smooth fracture. Note the difference in position and orientation compared to Figure 3.

DISCUSSION

Referring to Figure 1, the core of the software consists of linear algebra, computer graphics, mechanics of beams etc. These areas are considered to be problem free, since they have been tested rigorously. The areas which should be discussed are in the field of the limitations produced by the assumptions and abstractions used in the software.

One of these abstractions is that although muscles are described as separate functional units (masseter and temporalis muscles are split up in units), they still operate along single working lines and pull at discrete points of insertion. It can be shown that this is only a problematic abstraction if the fracture runs through an area of insertion of a muscle.

The calculation of the mechanical equilibrium of fracture and plates is performed using an elastic elements method with detailed representation of 3D fracture shape, with linear elastic bone properties and with energy minimum search. This represents a fairly realistic piece of modelling, but rests on the assumption of homogeneous bone properties, which we know is not natural. However, the properties of cortical bone have been used. Cortical bone takes up most of the task of compressive force resistance, since usually, a torque is also present at the fracture, resulting in slight tilting of one of the bone fragments relative to the other, so that the spongeous bone is not loaded (which is an important explanation of the human jaw having spongeous bone and a canal).

The search for the energy minimum of the combination of bones and plates is a trip through a rugged landscape with steep ravines, since only small movements of the bony halves can bring other parts of the fracture in contact with each other, resulting in quite different elastic energy values. The polytope search algorithm has surprising properties in taking care of such a hazardous journey.

The search for the optimal bone plate positions is more difficult, and proved to be impossible without the use of a grid search strategy described above. It appeared in most cases that a grid of six steps along the line of possible screw positions is sufficient to get an overview of the landscape for the polytope method to start its journey in a convenient spot. There are usually at least two solutions in the landscape of possibilities, of which one is the best.

Another assumption used is that the load on the fracture fragments and on the fixation plates is highest in isometric biting conditions. This assumption can be defended by indicating that even if maximum muscle recruitment accelerates a free hanging lower jaw, the load on the fracture will be less than in an isometric condition, since shortening muscles produce less force than isometrically active muscles.[33]

It was assumed that all jaw muscles have optimal sarcomere lengths in occlusion. This was done because of lack of data on this subject. It was not investigated how critical this assumption is for the loads across the fracture. It is expected that only in the case of masseter muscle (short fibers compared to leverage arm), it is critical to know sarcomere lengths of the functional units. Furthermore, if any of the balancing muscles has another maximum force than used in the present software, the recruitment pattern will be adjusted accordingly (because of the use of the linear programming method[17]), so no effect will be noticed at the site of the fracture. Only those muscles that are recruited maximally will have critical sarcomere lengths.

It is assumed that the temporomandibular joint load vectors have constant directions. This assumption is based on the work of Koolstra et al.[17] and is discussed in their papers. Tests with the recruitment model, with free temporomandibular joint vectors, indicated that extremely high biting forces can be generated if one of these joint vectors points at one of the frontal elements, counterbalanced by the bite vector pointing at the temporomandibular joints. This is not very realistic, since frontal elements are not well designed for carrying force vectors lying in a plane through the jaw joints. Presently we feel that no further refinement is required, given the detail (or lack of detail) in the other data.

A last assumption to be discussed here is that the 3D shape, orientation and position of a fracture can be indicated quite accurately. Clearly this depends very much on the quality of the standardized cephalometric roentgenographs used, and on interpretations and observations during exploration made by the surgeon. Perturbation analyses indicated that particularly the shape of the fracture is of importance. Usually, however the position and orientation of the fracture have a tolerance of about 5 mm and 10 degrees respectively (generating negligible differences in optimal plate positions and strains), but can be less robust in some cases.

With the software package 'JawKit' more than one fracture can be analyzed. This can be done sequentially for each fracture, since if one fracture is stabilized by a bone plate, the resulting combination of bony elements and plates is mechanically supposed to be equivalent to an unfractured bone. This implies that a second fracture can be analyzed as though the first one were not there.

Experiments with the software indicated that in all cases a complex load across the fracture occurs. This results in a failure of predictions of optimal bone plate positions based on the main load (ignoring the other load components), such as used by Champy.[5,34] A combination of loads (torques and forces at odd angles to the fracture) tends to lead to ill predictable bone plate positions, because such complex loads are hard to envisage in terms of mechanics and bone plate positions.

As described before, until now decisions on the choice and localization of bone plate systems have been based on models in which maximum generated bite forces were translated to dissected mandible halves or bars representing the mandible. In the present study a model has been developed in which it is possible to integrate the functional performance of the masticatory system, the individual morphology and the appearing fracture of the case at hand. This results in the directions and magnitudes of the muscle forces and joint loads which are acting on the bone and the bone plate. In advance, but preferably during the operation, the surgeon can decide on the device choice, optimal positioning and the amount of bone plates. Additionally, the data obtained from the model can be used in designing bone plate shape, dimensions and new materials.

REFERENCES

1 Brons R: Stabiele interne fixatie bij corpus mandibulafrakturen. Thesis. Groningen, University of Groningen, 1970, pp 84–97

2 Kárász I, Köröndi L, Szabó G: Photoelastic stress analysis on mandibular osteosynthesis. Int J Oral Maxillofac Surg 15: 259–262, 1986

3 Rahn B, Cordey J, Prein J, Russenberger M: Zur Biomechanik der Osteosynthese an der Mandibula. In: Spiessl B & Schuchardt K (eds): Fortschritte der Kiefer und Gesichts-Chirurgie Bd. 19. Thieme, Stuttgart, 1975, pp 37–42

4 Ewers R, Niederdellmann H: Spannungsoptische Untersuchungen bei der Verschraubung von Osteosyntheseplatten. Dtsch Zahnarztl Z 32: 349–352, 1977

5 Champy M, Lodde JP, Jaeger JH, Wilk A: Osteosynthèses mandibulaires selon la technique de Michelet. I. Bases biomécaniques. Rev Stomat 77: 569–576, 1976

6 Ralph JP and Caputo AA: Analysis of stress patterns in the human mandible. J Dent Res 54: 814–821, 1975

7 Niederdellmann H: Fundamentals of Healing of Fractures of the Facial Skull. In: Krüger E and Schilli W (Eds). Oral and Maxillofacial Traumatology 1. Quintessence Publishing Co, Inc, Chicago, Illinois, 1982, pp 125–133

8 Champy M, Pape H-D, Gerlach KL, Lodde JP: Mandibular fractures. In: Krger E, Schilli W and Worthington P. Oral and maxillofacial traumatology 2. Quintessence Publishing Co, Inc, Chicago, London, Berlin, Rio de Janeiro and Tokyo, 1986, pp 19–43

9 Barbenel JC: The biomechanics of the temporomandibular joint: a theoretical study. J Biomechanics 5: 251–256, 1972

10 Mansour MM, Reynik RJ: in *vivo* occlusal forces and moments: I. Forces measured in terminal hinge position and associated moments. J Dent Res 54: 114–120, 1975

11 Greaves WS: The jaw lever system in ungulates: a new model. J Zool 184: 271–285, 1978

12 Pruim GJ, Jongh de HJ, Bosch ten JJ: Forces acting on the mandible during bilateral static bite at different bite force levels. J Biomechanics 13: 755–763, 1980

13 Weijs WA: Mechanical loading of the human jaw joint during unilateral biting. Acta morph.neerl.-scand. 19: 261–262, 1981
14 Throckmorton GS and Throckmorton LS: Quantitative calculation of temporomandibular joint forces – I. The importance of the magnitude of the muscle forces. J Biomechanics 18: 445–452, 1985
15 Throckmorton GS: Quantitative calculations of temporomandibular joint reaction forces – II. The importance of the direction to the jaw muscle forces. J Biomechanics 18: 453–461, 1985
16 Osborn JW, Baragar FA: Predicted pattern of human muscle activity during clenching derived from a computer assisted model: symmetric vertical bite forces J Biomechanics 18: 599–612, 1985
17 Koolstra JH, Eijden van TMGJ, Weijs WA and Naeije M: A three-dimensional mathematical model of the human masticatory system predicting maximum possible bite forces. J Biomechanics 21: 563–576, 1988
18 Leenslag JW, Pennings AJ, Bos RRM, Rozema FR, Boering G: Resorbable materials of poly(L-lactide) VI. Plates and screws for internal fracture fixation. Biomaterials 8: 70–73, 1987
19 Bos RRM, Boering G, Rozema FR, Leenslag JW: Resorbable Poly(L-lactide) plates and screws for the fixation of zygomatic fractures. J Oral Maxillofac Surg 45: 751–753, 1987
20 Otten E: A myocybernetic model of the jaw system of the rat. J Neurosci Methods 21: 287–302, 1987
21 Otten E: Concepts and models of functional architecture in skeletal muscle. In: Kent BR, PhD (Ed), Exercise and Sport Science Reviews, MacMillan, New York, pp 89–139, 1988
22 Otten E, Leeuwen van J: MacReco, a 3D reconstruction package from serial sections and images. Eur J Cell Biol 48: 73–77, 1988
23 Weijs WA, Hillen B: Relationships between the masticatory muscle cross-section and skull shape. J Dent Res 63: 1154–1157, 1984
24 Eijden van TMGJ: pers comm. Academic Center for Dentistry Amsterdam (ACTA), The Netherlands
25 Press WH, Flannery BP, Teukolsky SA and Vetterling WT: Numerical Recipes. Cambridge University Press, Cambridge, 1987
26 Popov EP: Mechanics of Materials. Prentice Hall, Englewood Cliffs, New Jersey, 1978
27 Ashman RB, Buskirk van WC: The elastic properties of the human mandible. Adv Dent Res 1: 64–68, 1987
28 Nelder JA, Mead R: A simplex method for function minimization. Comp J 7: 308–313, 1965
29 Leenslag JW, Pennings AJ, Bos RRM, Rozema FR, Boering G: Resorbable materials of poly(L-lactide) VII. In *vivo* and in *vitro* degradation. Biomaterials 8: 311–314, 1987
30 Bos RRM, Rozema FR, Boering G, Nijenhuis AJ, Pennings AJ and Verweij AB: Bone plate and screws of bio-absorbable poly(L-lactide). An animal pilot study. Br J Oral Maxillofac Surg 27: 467–476, 1989
31 Bos RRM, Rozema FR, Boering G, Nijenhuis AJ, Pennings AJ, Verweij AB: Bio-absorbable plates and screws for internal fixation of mandibular fractures. A study in 6 dogs. Int J Oral Maxillofac Surg 18: 365–369, 1989
32 Gerlach KL, Pape H-D, Nussbaum P: Untersuchungen zur Belastbarkeit der Miniplattenosteosynthese von Unterkieferfrakturen. Dtsch Z Mund Kiefer GesichtsChir 8: 363–366, 1984
33 Hill AV: The heat of shortening and the dynamic constants of muscle. Proc R Soc London Ser B 126: 136–195, 1938
34 Lodde JP, Champy M: Justification biomécanique d'un nouveau matériel d'ostéosynthèse en chirurgie faciale. Ann Chir Plast 21: 115–121, 1976